Physics Potential of a 2540 Km Baseline Superbeam Experiment

Aniket Joglekar[*], Suprabh Prakash, Sushant K. Raut,[†] and S. Uma Sankar

Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India

Abstract

We study the physics potential of a neutrino superbeam experiment with a 2540 km baseline. We assume a neutrino beam similar to the NuMI beam in medium energy configuration. We consider a 100 kton totally active scintillator detector at a 7 mr off-axis location. We find that such a configuration has outstanding hierarchy discriminating capability. In conjunction with the data from the present reactor neutrino experiments, it can determine the neutrino mass hierarchy at 3σ level in less than 5 years, if $\sin^2 2\theta_{13} \geq 0.01$, running in the neutrino mode alone. As a stand alone experiment, with a 5 year neutrino run and a 5 year anti-neutrino run, it can determine non-zero θ_{13} at 3σ level if $\sin^2 2\theta_{13} \geq 7 \times 10^{-3}$ and hierarchy at 3σ level if $\sin^2 2\theta_{13} \geq 8 \times 10^{-3}$. This data can also distinguish $\delta_{CP} = \pi/2$ from the CP conserving values of 0 and π, for $\sin^2 2\theta_{13} \geq 0.02$.

[*] Address after August 1, 2010: Department of Physics, University of Chicago, Chicago, IL, USA

[†] Email Address: sushant@phy.iitb.ac.in

I. INTRODUCTION

During the past decade, great progress has been made in the study of neutrinos. In particular, the mass-squared differences and two of the mixing angles have been measured with good precision. Despite this progress, the following properties of neutrinos are still unknown

- The absolute mass scale of the neutrinos,

- Dirac vs Majorana nature of neutrinos,

- The value of the mixing angle θ_{13},

- Mass pattern or mass hierarchy of the neutrinos,

- CP violation in neutrino sector and the value of the CP-violating phase δ_{CP},

- Deviation of θ_{23} from $\pi/4$.

KATRIN tritium decay experiment [1, 2] and various neutrinoless double beta decay experiments [3] currently underway will address the first two problems. The next four problems fall under the purview of neutrino oscillations and hence are expected to be solved by the current and future neutrino oscillation experiments. There are three efforts underway to determine the mixing angle θ_{13} using reactor neutrino data. They are (a) Double Chooz, expected to start taking data this year [4] with sensitivity $\sin^2 2\theta_{13} \geq 0.04$, (b) RENO [5] with sensitivity $\sin^2 2\theta_{13} \geq 0.02$, and (c) Daya Bay [6] with sensitivity $\sin^2 2\theta_{13} \geq 0.01$. In addition, there are two accelerator experiments, T2K and NOνA, which can determine non-zero θ_{13}. Their sensitivities are $\sin^2 2\theta_{13} \geq 0.01$ at 90% confidence level for T2K [7] and $\sin^2 2\theta_{13} \geq 0.03$ at 3σ for NOνA [8]. Thus it is hoped that the determination of θ_{13} can be achieved by these experiments within the next decade.

However, it was shown recently [9] that the currently running or planned experiments will be able to determine the mass hierarchy or δ_{CP} only for very favourable values of θ_{13} and δ_{CP}. The effect of mass hierarchy and δ_{CP} are closely interlinked [10–14]. Disentangling these two effects requires considerable effort and possibly data from many experiments [15, 16]. Thus the question of designing a neutrino beam-detector configuration, which will enable us to determine hierarchy and δ_{CP} unambiguously, acquires great importance.

There have been numerous proposals made to achieve the above purpose. These include megaton size detectors [17–19], a pair of detectors with different baselines but with the same value of L/E [15, 16] and detectors at the 'magic' baseline of 7500 km [20, 21]. Recently we made a proposal of a shorter magical baseline [22], which has exceptional capability to determine mass hierarchy, independently of δ_{CP}. In this report, we study the full physics potential of our proposal.

II.   CALCULATION

As mentioned before, the unknowns to be determined from the neutrino oscillation experiments are the mixing angle θ_{13}, the neutrino mass hierarchy, the CP violating phase δ_{CP} and the octant of θ_{23}. The $\nu_\mu \rightarrow \nu_e$ oscillation probability $P_{\mu e}$ is sensitive to all these unknowns. In this paper, we will not consider the problem of octant ambiguity of θ_{23}. We will assume the true value of θ_{23} to be its best fit value $\pi/4$. The expression for $P_{\mu e}$, in three flavour oscillations including matter effects, is given as [23–25]

$$
\begin{aligned}
P_{\mu e} = & \, C_0 \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
& + \alpha \, C_1 \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \, \frac{\sin(\hat{A}\Delta)}{\hat{A}} \\
& + \alpha^2 C_2 \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned} \tag{1}
$$

where $\Delta = (1.27\Delta_{31}L/E)$, $\hat{A} = A/\Delta_{31}$ and $\alpha = \Delta_{21}/\Delta_{31} \approx \pm 0.04$, as given by the solar and atmospheric neutrino data [26]. Here L is in km, E is in GeV and Δ_{31} is given in units of eV^2. The coefficients, C_i are given by

$$
C_0 = \sin^2 \theta_{23} \sin^2 2\theta_{13} , \tag{2}
$$

$$
C_1 = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) , \tag{3}
$$

$$
C_2 = \sin^2 2\theta_{12} \cos^2 \theta_{23} . \tag{4}
$$

The matter effects are given by the matter term [27] A (in eV^2) $= 0.76 \times 10^{-4} \, \rho$ (gm/cc) E (GeV) eV^2. ρ is the density of the matter through which the neutrino propagates. Δ_{31} and hence Δ are positive for normal hierarchy (NH) and negative for inverted hierarchy (IH), for both neutrinos and anti-neutrinos. A, on the other hand, is

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positive for neutrinos and negative for anti-neutrinos. Therefore, $\hat{A}$ is positive for NH and negative for IH in the case of neutrinos, and vice versa for anti-neutrinos.

The dependence of $P_{\mu e}$ on δ_{CP} and θ_{13} is seen explicitly in Eq. (1). In addition, the quantities $\hat{A}$ and Δ are sensitive to the neutrino mass hierarchy. Thus, this channel which is sensitive to all the three unknowns mentioned above, is a good candidate to probe these unknown parameters. From Eq. (1) we see that $P_{\mu e}$ is large for $\Delta = (1.27\Delta_{31}L/E) \approx \pi/2$. On the other hand, the matter term $\hat{A}$ becomes significant at large energies. Therefore, the matter term starts to play an important role in shaping the oscillation probabilities only for long baselines. For a baseline of 732 km, and for fixed values of θ_{13} and δ_{CP}, it increases $P_{\mu e}$ by about 25% for NH and decreases it by the same amount for IH [28]. For longer baselines, the change in the probability is even larger. At shorter baselines, the sensitivity of $P_{\mu e}$ to the matter term and hence the mass hierarchy, is low.

Since $P_{\mu e}$ depends on three unknowns, θ_{13}, mass hierarchy and δ_{CP}, it is impossible to determine any one of them by making a single measurement. Even if one measures $P_{\mu e}$ as a function of energy, it is possible to get degenerate solutions [10–14]. For example, it is possible to have $P_{\mu e}(\theta_{13}, NH; E) = P_{\mu e}(\theta'_{13}, IH; E)$, as illustrated in Fig 1. Such a degeneracy can be broken, if the value of θ_{13} can be determined from different experiments. Reactor anti-neutrino experiments with $L \approx 1$ km, can determine θ_{13} unambiguously. The currently planned experiments can measure non-zero values as small as $\sin^2 2\theta_{13} \geq 0.01$ [4–6]. Thus we expect that this degeneracy can be lifted by the results of reactor neutrino experiments.

Even if the ambiguity due to the value of θ_{13} is lifted, there is a further ambiguity between hierarchy and δ_{CP}. This ambiguity arises due to the following reason. If we replace $\nu \to \bar{\nu}$, we have $\delta_{CP} \to -\delta_{CP}$ and $\hat{A} \to -\hat{A}$. However, if we flip the hierarchy, we have $\hat{A} \to -\hat{A}$ and $\Delta \to -\Delta$. Hence, the change in $P_{\mu e}$ due to hierarchy flip can be compensated by changing δ_{CP}. This ambiguity is particularly important for $\sin^2 2\theta_{13} \leq 0.02$. Therefore, even if we know the value of θ_{13}, it is possible to get degenerate solutions of the kind $P_{\mu e}(NH, \delta_{CP}; E) = P_{\mu e}(IH, \delta'_{CP}; E)$ over a wide range of energies, as illustrated in Fig. 2. We are led to consider various improvisations to overcome this problem.

In Eq. (1), only the C_1 term contains δ_{CP}. The hierarchy-δ_{CP} ambiguity can be lifted if the term containing C_1 can be chosen to be zero. One simple way to do it is to choose $\hat{A}\Delta = \pi$ [29]. This condition can be achieved for both NH and IH simultaneously and gives us
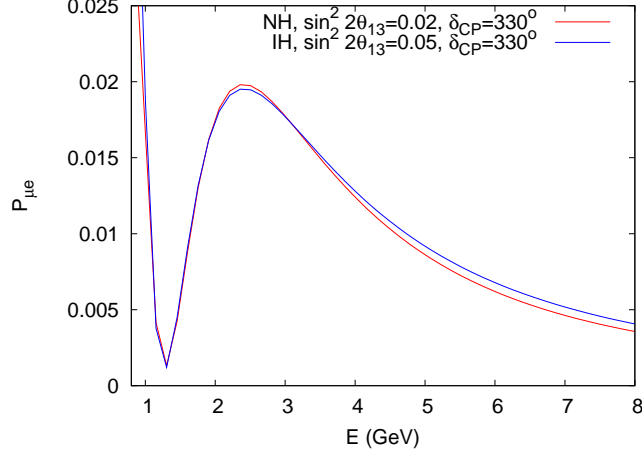
FIG. 1: Hierarchy-θ_{13} degeneracy in $P_{\mu e}$ at 1300km. We see that $P_{\mu e}(NH, \sin^2 2\theta_{13} = 0.02; E) = P_{\mu e}(IH, \sin^2 2\theta_{13} = 0.05; E)$. The value of δ_{CP} is taken to be 330° here.
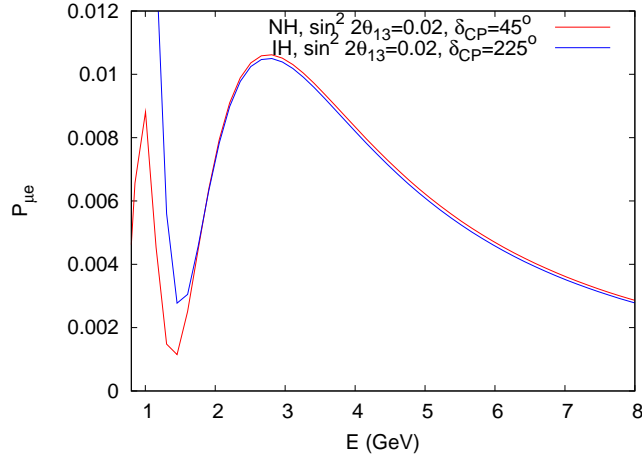

FIG. 2: Hierarchy-δ_{CP} degeneracy in $P_{\mu e}$ at 1300km. We see that $P_{\mu e}(NH, \delta_{CP} = 45°; E) = P_{\mu e}(IH, \delta_{CP} = 225°; E)$ for $E > 1.5$ GeV. The value of $\sin^2 2\theta_{13}$ is taken to be 0.02 here.

an energy independent condition $L \approx 7500$ km. This is the famous magic baseline condition and it has been extensively studied [20, 21]. In [22] it was noted that the C_1 term can be made zero for IH only by choosing $(1 - \hat{A})\Delta = -\pi$. This makes $P_{\mu e}(IH)$ independent of δ_{CP} and also very small ($\leq \alpha^2 \approx 0.002$). If we choose $(1 - \hat{A})\Delta = \pi/2$ for NH, then $P_{\mu e}(NH)$ will be quite siginificant for all values of δ_{CP}. Solving the above pair of simultaneous equations, we obtain $L = 2540$ km and $E = 3.3$ GeV. For this baseline, at this energy, there is a clear
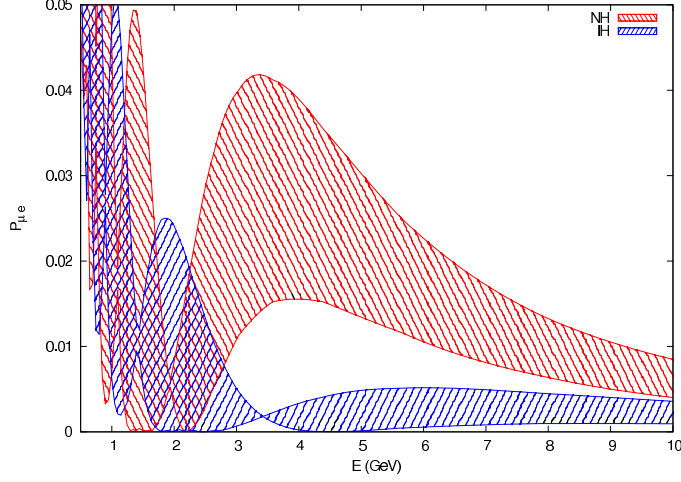
FIG. 3: $P_{\mu e}$ as a function of E for $L = 2540$ Km and $\sin^2 2\theta_{13} = 0.02$. $P_{\mu e}$ is plotted for both NH and IH, each for the full range of values of δ_{CP}.

separation between $P_{\mu e}(NH)$ and $P_{\mu e}(IH)$ as illustrated in Fig. 3. This is true for values of θ_{13} at least as small as those detectable by the current reactor experiments. In addition, $P_{\mu e}(NH)$ retains its dependence on δ_{CP} unlike in the magic baseline case. This, in turn, can be helpful in measuring δ_{CP} [30].

In our calculations, we have considered a superbeam experiment with a baseline of 2540 km. Note that the distance from Brookhaven Laboratory to Homestake mine [17, 18] and that from CERN to Pyhasalmi [31] are close to our shorter 'magical' baseline. Since our energy range of interest is around $3 - 4$ GeV, the neutrino source must have unoscillated event spectrum peaking in this energy range. The NuMI beam in the medium energy option has an unoscillated event spectrum that peaks at 3.5 GeV for locations 7 mr off the beam axis [8].

III.   RESULTS

We have done all our calculations using the software package GLoBES [32, 33]. The source is taken to be a NuMI like beam in the medium energy configuration. The detector is assumed to be a 100 kton totally active scintillator detector whose capabilities are similar to NOνA. Such a detector is placed at a distance 2540 km from the source at a 7 mr off-axis location. The fluxes for this location were calculated using the program from [34]. The beam

power is taken to be such that it corresponds to 10×10^{20} POT/yr. This is about 30% more than the design power for NOνA. Thus we have an exposure of 1000×10^{20} kton-POT/yr. This is about 10 times larger than the exposure for NOνA. The baseline in our proposal is thrice as long as that of NOνA. Hence the factor 10 increase in exposure makes the data to have the same statistical weight as that of NOνA.

We have computed the ν_e appearance spectrum in the detector for the energy range from 250 MeV to 10 GeV, in bins of 250 MeV width. A Gaussian energy smearing function with a width of $0.1\sqrt{E\ (GeV)}$ has been assumed for these events. We have considered four different types of events in our analysis: signal ($\nu_\mu \rightarrow \nu_e$) events, beam background events (that is, events caused by intrinsic ν_e component of the beam), background events due to misidentified muons and the background events due to neutral current interactions. Energy independent cuts identical to those for NOνA have been imposed on these channels, which substantially enhance the signal to background ratio [8, 35].

In our calculations, the solar parameters $\sin^2 \theta_{12} = 0.304$ and $\Delta_{21} = 7.65 \times 10^{-5} eV^2$ have been kept fixed throughout [26, 36, 37]. The values of Δ_{31} and θ_{23} are taken from three flavour oscillation fit of the atmospheric [38] and MINOS data [39]. We take the true value of $\sin^2 2\theta_{23}$ to be its best fit value 1. We assumed an error of 2% on this measurement. Hence the test values of θ_{23} are to be chosen to satisfy the constraint $0.94 \leq \sin^2 2\theta_{23} \leq 1$. Thus we have the range $38° \leq \theta_{23} \leq 52°$. The situation regarding Δ_{31} is a bit more complicated. The most accurate measurement of the larger mass-squared difference is given by the MINOS experiment [39]. If the results of MINOS are interpreted in terms of three flavour oscillations, the effective mass-squared difference measured by it is not $|\Delta_{31}|$ but is the magnitude of a linear combination of Δ_{31} and Δ_{21} [40, 41]. It is shown [41] that the linear combination is of the form $\Delta_{31} + \Delta_{21} f(\theta_{ij}, \delta_{CP})$, where

$$f(\theta_{ij}, \delta_{CP}) = \cos^2 \theta_{12} - \cos \delta_{CP}\ \sin \theta_{13}\ \sin 2\theta_{12}\ \tan \theta_{23}. \tag{5}$$

In computing $P_{\mu e}$(NH) and $P_{\mu e}$(IH) we must relate the corresponding values of Δ_{31} via

$$\Delta_{31}\ (\text{IH}) = -\Delta_{31}\ (\text{NH}) - 2\Delta_{21} f(\theta_{ij}, \delta_{CP}), \tag{6}$$

rather than as Δ_{31} (IH) $= -\Delta_{31}$ (NH). If we were to take Δ_{31} (IH) $= -\Delta_{31}$ (NH), then we would get a significant *fake hierarchy sensitivity* in the ν_μ disappearance channel, even for very small values of θ_{13}. In our calculations, we have related Δ_{31} (NH) and Δ_{31} (IH) via

Eq.(6), and used the best fit value Δ_{31} (NH) $= 2.4 \times 10^{-3} eV^2$, with an error of 5%. The systematic errors include a 5% normalization error and 2.5% tilt error on both the signal and the background. We have also taken into consideration a 5% error in the density profile of the earth.

First we computed the hierarchy sensitivity of this setup, running it in the neutrino mode only. In this part of the calculation, we limited ourselves to the range $0.01 \leq \sin^2 2\theta_{13} \leq 0.1$. That is, we assumed that this parameter will be determined by one of the current experiments. First we assumed NH to be the true hierarchy and computed the χ^2 for distinguishing this from IH, as a function of $\sin^2 2\theta_{13}$. In computing the χ^2, we combined the results of our proposed set up with those of the reactor experiments and of T2K and NOνA [7, 8, 35, 42–44]. The data from the reactor experiments provide a 'prior' on the values of $\sin^2 2\theta_{13}$. In computing χ^2, we have marginalized over the range $0.01 \leq \sin^2 2\theta_{13} \leq 0.1$. We have varied the CP phase over the full range $-\pi \leq \delta_{CP} \leq \pi$ in computing the event rates both for NH and for IH. We have then repeated the above calculation, this time assuming IH to be the true hierarchy. The results of these calculations are tabulated in Table I. We indicate here the exposure time (in years) required for hierarchy discrimination up to a 3σ confidence level as a function of $\sin^2 2\theta_{13}$.

From the results of the table, it is worth remarking that, the present 15 kton NOνA detector, with its current design luminosity, can determine the neutrino mass hierarchy, independently of δ_{CP}, in a five year neutrino run, if $\sin^2 2\theta_{13} \geq 0.03$, were the detector placed at a distance of 2540 km with an appropriately designed beamline.

Next, we have calculated the ability of our setup (in conjunction with T2K, NOνA and the reactor experiments) to determine δ_{CP} as a function of $\sin^2 2\theta_{13}$. In addition to the data from a five year neutrino run, we assume data from a five year anti-neutrino run. We have chosen fifteen different pairs of true values of $\sin^2 2\theta_{13}$ and δ_{CP} given by $\sin^2 2\theta_{13} = 0.01, 0.05, 0.10$ and $\delta_{CP} = -160°, -80°, 0°, 80°, 160°$. We assumed normal hierarchy and computed the allowed 1σ and 2σ regions in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane. In Figure 4, we have plotted the outer contours of these allowed regions, corresponding to the fifteen different true parameter sets. The panel on the left gives the results including the systematic errors, whereas the panel on the right shows the allowed contours without the systematic errors. From the right panel, we see that the allowed regions are very close to the true values and the value of

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$\sin^2 2\theta_{13}$ (true)	Exposure time(NH)	Exposure time(IH)
0.10	0.022	0.048
0.09	0.026	0.057
0.08	0.031	0.068
0.07	0.040	0.082
0.06	0.051	0.105
0.05	0.070	0.137
0.04	0.104	0.195
0.03	0.180	0.420
0.02	0.425	2.600
0.01	2.950	4.800

TABLE I: Exposure time in years required for 3σ hierarchy discrimination, for 1000×10^{20}kton-POT/yr. The second (third) column shows the results if NH (IH) is the true hierarchy. It is assumed that the experiment runs in neutrino mode only.

δ_{CP} can be determined with an uncertainty of about $10°$. The value of $\sin^2 2\theta_{13}$ is rather tightly constrained by the data from reactor neutrino experiments. However, the inclusion of systematic errors makes the allowed regions considerably larger. $\sin^2 2\theta_{13}$ is allowed to deviate from its true value by about 0.005 and the uncertainty in determining δ_{CP} rises to about $20°$.

We have also computed the physics capabilities of the proposed setup as a stand alone experiment. As mentioned before, in the previous calculations, we have taken a lower limit of $0.01 \leq \sin^2 2\theta_{13}$. The reason for this is, that for values of θ_{13} above this limit, the data from the reactor experiments provide a 'prior'. In the calculations discussed below, we did not impose this lower limit on θ_{13} but allowed it to be as small as $\sin^2 2\theta_{13} \simeq 10^{-4}$.

In computing the results discussed below, we have assumed a 5 year neutrino and a 5 year anti-neutrino run. Based on this data, we computed the sensitivity of this set up to
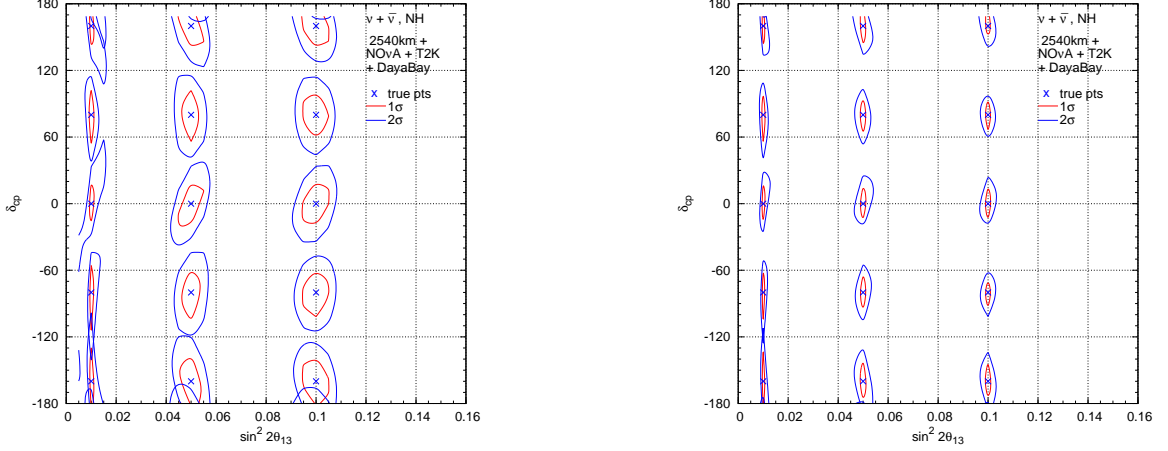
- measure non-zero θ_{13}

- determine hierarchy

FIG. 4: 1σ and 2σ contours for sensitivity in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane. The plot on the right is without systematics.

- rule out the CP conserving value of $\delta_{CP} = 0$ or π.

In figure 5, we plot the true values of $\sin^2 2\theta_{13}$ for which this parameter can be distinguished from 0. We do this as a function of the true value of δ_{CP} for both NH and IH. If NH is the true hierarchy, then values of $\sin^2 2\theta_{13}$ as small as 8×10^{-4} can be measured at 3σ level, for advantageous values of δ_{CP} (between $-\pi/3$ to $-2\pi/3$). For adverse values of δ_{CP} (between $\pi/6$ to $\pi/2$), however, θ_{13} can be distinguished from 0 only for $\sin^2 2\theta_{13} \geq 7 \times 10^{-3}$. If IH is the true hierarchy, the results are similar, except for the fact that the advantageous and adverse values of δ_{CP} are exchanged.

In figure 6, we plot the sensitivity of this setup for distinguishing the mass hierarchy as a function of the true value of $\sin^2 2\theta_{13}$ and δ_{CP}. Once again, for advantageous values of δ_{CP}, the mass hierarchy can be determined at 3σ for $\sin^2 2\theta_{13} \geq 8 \times 10^{-4}$, whereas for adverse values, it can be determined only for values which are about an order of magnitude larger.

Here we must insert a note of caution. Figures 5 and 6 give the sensitivity of our proposed setup as a function of the true value of δ_{CP}. However, the true value of δ_{CP} is unlikely to be known from any of the current experiments. Hence, while making a statement regarding the sensitivity of our setup, we must consider the most advserse value of δ_{CP}. Thus, a five year neutrino and a five year anti-neutrino run in our setup can measure, *independently of* δ_{CP}, $\sin^2 2\theta_{13}$ if it is larger than 7×10^{-3} and it can determine hierarchy for a similar lower limit on θ_{13}.

Finally, figure 7 shows the ability of the setup to exclude the CP-conserving case, $\delta_{CP} =$

$0, \pi$. We find that the maximal phase $\delta_{CP} = \pm\pi/2$ can be distinguished from $\delta_{CP} = 0, \pi$ for $\sin^2 2\theta_{13} \geq 0.01$. But for other values, discrimination from CP conserving case is possible only for larger values of θ_{13}. In fact, for δ_{CP} outside the two ranges $-2\pi/3$ to $-\pi/3$ and $\pi/3$ to $2\pi/3$, the discrimination from CP conserving case is not possible even for the largest allowed value of θ_{13}.

H2B collaboration [45] have considered a neutrino superbeam experiment with a baseline in excess of 2000 km. Their setup envisaged directing a 4 MW neutrino superbeam, with peak flux at $E_\nu = 4$ GeV, from Tokai in Japan to a 100 kton water Cerenkov detector at Beijing, 2100 km away. Such a set up is close to satisfiying the shorter magic baseline conditions derived in section-II. They found that [46, 47] such a setup, running only in neutrino mode for five years, can determine mass hierarchy for all values of δ_{CP}, if $\sin^2 2\theta_{13} \geq 0.02$.

There was a previous study of a superbeam proposal with 2540 km baseline [17, 18]. In this proposal, a wide band neutrino beam, with $0.5 \leq E_\nu \leq 7$ GeV energy range from Brookhaven National Laboratory is directed at a 500 kton water Cerenkov detector at Homestake mine. The beam is expected to be produced by 28 GeV protons with 1 MW intensity. This corresponds to 22×10^{20} POT/yr assuming one year contains 10^7 sec running time [48, 49]. The detector is assumed to be along the beamline, rather than at an off-axis location, which leads to the rather wide range in the energy. With a 5 year run in neutrino mode only, this setup can set a 90% confidence level upper limit $\sin^2 2\theta_{13} \leq 0.005$ if NH is the true hierarchy and $\sin^2 2\theta_{13} \leq 0.02$ if IH is the true hierarchy. It can also determine δ_{CP} with about a 25% uncertainty.

A few years ago, a US long baseline neutrino study group advocated a 1300 km baseline experiment to determine the unknown neutrino parameters from oscillations [48, 49]. They considered a wide band neutrino beam with $0.25 \leq E_\nu \leq 7$ GeV energy range directed from Fermilab to a 300 kton water Cerenkov detector at Homestake mine. They assumed a neutrino run with 30×10^{20} POT with a similar anti-neutrino run. The exposure of this setup, in POT-kton, is twice that of the setup we considered. The CP-violation discovery potential of this setup is better but the hierarchy determination potential of our proposal is better [50].

Recently, there was another study which considered additional magical properties of the 2540 km baseline [30]. In that study, the following set up was considered. The neutrino source is a low energy neutrino factory with a flux of 5×10^{21} muons/year with the muon

energy of 5 GeV. The detector is a 25 kton totally active scintillator detector and it is assumed that this setup will run with positive muons for 2.5 years. With these beam and detector specifications, the authors showed that θ_{13} can be measured for values $\sin^2 2\theta_{13} \geq 4 \times 10^{-3}$ and the hierarchy can be determined for $\sin^2 2\theta_{13} \geq 8 \times 10^{-3}$. This set up seems to have a good ability to discover non-zero δ_{CP}.
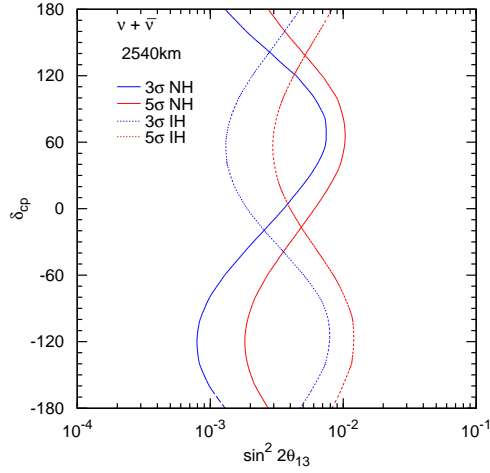

FIG. 5: 3σ and 5σ contours in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane for excluding $\theta_{13} = 0$.

IV. CONCLUSION

In an earlier paper, we demonstrated that a neutrino superbeam experiment with a 2540 km baseline is particularly well suited to determine neutrino mass hierarchy, independently of the value of δ_{CP}. In this paper, we performed a full-fledged study of the physics potential of such an experiment. We considered a 100 kton totally active scintillator (NOνA like) detector with the neutrino source being a NuMI-like beam in medium energy option with
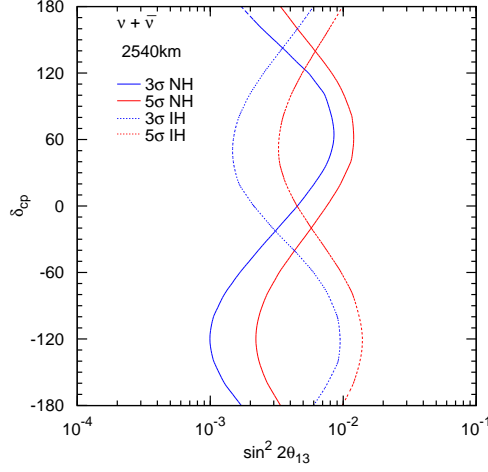
FIG. 6: 3σ and 5σ contours in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane for excluding the 'wrong' hierarchy.
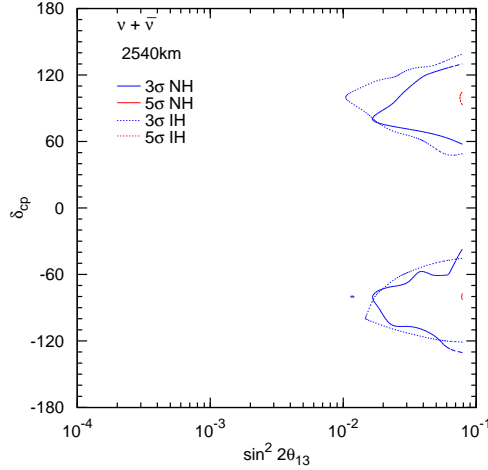

FIG. 7: 3σ and 5σ contours in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane for excluding CP conservation.

10×10^{20} POT/yr. We performed the analysis using GLoBES software, where all the appropriate background events have been included and background suppression factors relevant for NOνA are imposed. We demonstrate that a five year neutrino run in this setup, together with data from reactor neutrino experiments, can determine the neutrino hierarchy *independently* of δ_{CP} for $\sin^2 2\theta_{13} \geq 0.01$. This statement holds irrespective of whether the true

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hierarchy is NH or IH. With additional data from a five year anti-neutrino run, this setup is capable of determining δ_{CP} with an uncertainty of about $20°$.

If this setup is considered by itself, then the data from a five year neutrino run plus a five year anti-neutrino run can measure non-zero θ_{13} and determine neutrino mass hierarchy for $\sin^2 2\theta_{13} \geq 7 \times 10^{-3}$. These statements hold true for all possible values of δ_{CP}. It is also possible to obtain signals for CP violation, for moderately large values of $\sin^2 2\theta_{13}$.

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